7 SOIL SALINITY AND SODICITY

Saline/sodic soils contain either elevated levels of Ca or Na or both; those having high Na levels (sodic soils) may have pH values 8.5 or above. When soil pH is as high as 8.5, a number of micronutrients such as Fe, Mn, Cu, and Zn become deficient and crop growth is adversely affected. Also high Na concentrations damage plant roots and affect plant growth adversely. In addition, sodic soils with more than about 20% clay content exhibit poor physical structure as a result of the destruction of aggregation resulting from adsorption of the hydrated Na^+ ions on clay surfaces. These soils crust and cake, have low infiltration rates, and are a poor medium for plant growth. Sodic soils may or may not be high in total soluble salts (saline).

Saline soils are high in concentration of soluble salts and are alkaline if Mg or Na are the dominant cations. However, saline soils may also be high in exchangeable H^+ with pH as low as 4.0, presenting severe soil acidity problems that affect nutrient availability as discussed in Chapter 6. Salinity experiments with cereals conducted in field plots at constant fertilizer application (Francois et al., 1986) demonstrate a 20 to 50% reduction in plant P content. On the other hand, Grattan and Maas (1984) observed P toxicity for soybeans under saline conditions in a solution culture at P levels that were nontoxic under nonsaline conditions. These data indicate the intricacies of soil fertility problems as influenced by salinity. An understanding of the nature of soil salinity/alkalinity can therefore greatly help in soil fertility management on such soils.

7.1. COVERAGE AND SPECIAL FEATURES

Large land masses, particularly in the arid and semiarid regions of the world, have salt deposits in the soil surface during hot summer periods. These salts may move to the subsoil during the rains and may move again to the surface during dry periods. Depending upon the salts present, these soils may have problems of acidity or alkalinity. Also, if Na salts dominate, degraded soil structure may create additional problems. The world distribution of salt-affected areas is given in Table 7.1.

Table 7.1 The World Distribution of Salt-Affected Areas (1000 ha)

Continent	Country	Saline/ solonchaks	Sodic/ solonetz	Total
North America	Canada	264	6974	7238
	United States	5927	2590	8517
Mexico and Central America	Cuba	316	—	316
	Mexico	1649	—	1649
South America	Argentina	32473	55139	85612
	Bolivia	5233	716	5949
	Brazil	4141	362	4503
	Chile	5000	3642	8642
	Colombia	907	0	907
	Ecuador	387	—	387
	Paraguay	20008	1894	21902
	Peru	21	—	21
	Venezuela	1240	0	1240
Africa	Afars and Issas	1741	—	1741
	Algeria	3021	129	3150
	Angola	440	86	526
	Botswana	5009	670	5679
	Chad	2417	5850	8267
	Egypt	7360	0	7360
	Ethiopia	10608	425	11033
	Gambia	150	0	150
	Ghana	200	118	318
	Guinea	525	—	525
	Guinea-Bissau	194	—	194
	Kenya	4410	448	4858
	Liberia	362	44	406
	Libyan Arab Jamahiriya	2457	—	2457
	Madagascar	37	1287	1324
	Mali	2770	0	2770
	Mauritania	640	—	640
	Morocco	1148	—	1148
	Namibia	562	1751	2313
	Niger	—	1389	1389
	Nigeria	665	5837	6502
	Rhodesia	—	26	26
	Senegal	765	—	765
	Sierra Leone	307	—	307
	Somalia	1569	4033	5602

Table 7.1 The World Distribution of Salt-Affected Areas (1000 ha) (Continued)

Continent	Country	Saline/ solonchaks	Sodic/ solonetz	Total
	Sudan	2138	2736	4874
	Tunisia	990	—	990
	United Rep. of Cameroon	—	671	671
	United Rep. of Tanzania	2954	583	3537
	Zaire	53	—	53
	Zambia	—	863	863
Southern Asia	Afghanistan	3103	—	3103
	Bangladesh	2479	538	3017
	Burma	634	—	634
	India	23222	574	23796
	Iran	26399	686	27085
	Iraq	6726	—	6726
	Israel	28	—	28
	Jordan	180	—	180
	Kuwait	209	—	209
	Muscat ant Oman	290	—	290
	Pakistan	10456	—	10456
	Qatar	225	—	225
	Sarawak	1538	—	1538
	Saudi Arabia	6002	—	6002
	Sri Lanka	200	—	200
	Syrian Arab Rep.	532	—	532
	United Arab Emirates	1089	—	1089
North and Central Asia	China	36221	437	36658
	Mongolia	4070	—	4070
	USSR	51092	119628	170720
Southeast Asia	Democractic Kampuchea	1291	—	1291
	Indonesia	13213	—	13213
	Malaysia	3040	—	3040
	Socialist Rep. of Vietnam	983	—	983
	Thailand	1456	—	1456
Australasia	Australia	17269	339971	357240
	Fiji	90	—	90
	Solomon Islands	238	—	238

From Massoud, 1977. Proc. Int. Conf. Managing Saline Water. 1976, pp. 432–454. Texas Tech. University Press, Lubbock, TX.

Salt-affected soils are drawing more and more global attention because of population pressure and the consequent ever-increasing food demands in some regions of the world where such soils exist. Heavy food demand has necessitated the development of irrigation in such areas. Without adequate provisions for drainage, irrigation has aggravated the situation of salinity/alkalinity. For food production, these soils are regarded as a class of problem soils that need special remedial measures and management practices. Composition of salts, their distribution in the profile, soil texture and structure, and the species of plants grown determine plant growth on these soils.

The main source of all salts in the soil is the primary minerals of the earth's crust, which are gradually released and made soluble during chemical weathering. In some regions salts are transported away from their source of origin in humid areas through surface and groundwater streams to semiarid and arid regions. These salts may then move up to the soil surface by capillary movement due to high evaporation rates resulting from the high temperatures of such regions.

The predominant ions at the site of weathering are carbonates, bicarbonates, sulfates, and chlorides of Ca, Mg, K, and Na. Often, as these salts move down the stream, those with low solubility are precipitated, while others undergo further changes through processes of exchange, adsorption, and differential mobility. The net result is that many Ca and Mg salts are removed, leaving high concentration of chloride and sodium ions. In some regions the ocean may be the source of salts, and parent material consists of marine deposits. The Mancos shales occurring in Colorado, Wyoming, and Utah are typical examples of saline marine deposits. Also the low-lying soils along the sea coasts, such as the Kari soils in Kerela (India), get their salts from the ocean. Sometimes, salt is moved inland through the transportation of spray by winds (cyclic salt) or by flooding following hurricanes. These soils are less extensive and have special problems. The discussion in this chapter is restricted to large areas, where the source of salts is surface and groundwaters.

When soils have an excess of chlorides and sulfates, during dry periods these salts are often deposited on the surface giving a white appearance. Such soils have been called "white alkali soils." Truly speaking, they are not alkali soils and should be called saline soils. The presence of high concentrations of carbonates and bicarbonates of Na is generally associated with dispersed humus in the surface soil, which appears black. Hence, the name "black alkali soils" (now known as sodic soils) has been given, because Na is the element responsible for several of their properties. It is desirable to differentiate between sodic and saline soils as the management practices required for them differ markedly. There are three criteria that are used for determining and classifying salinity and sodicity. These are (1) salt concentration, (2) sodium status, and (3) pH. A brief discussion on these follows.

7.2. CRITERIA FOR DETERMINING SALINITY/SODICITY

1. Salt concentration: Salt concentration in soil solution is determined based on the principle of the ability of salt to conduct electricity. This determination is thus made on a soil slurry or saturation extract with a conductivity meter. Electrical conductivity (EC_e or sometimes EC) is measured in decisemens per meter (dS m^{-1}). An earlier unit of measurement was millimhos per centimeter (mmhos cm^{-1}). Since 1 siemen(s) = 1 mho = 1000 mmhos, then 1 dS = 100 mmhos. Thus, 1 dS m^{-1} = 100 mmhos m^{-1} = 1 mmho cm^{-1}. Some useful conversion factors are given in Table 7.2.

Table 7.2 Some Useful Conversion Factors

- Conductivity 1 S cm^{-1} (1 mho/cm) = 1000 mS/cm (1000 mmhos/cm)

  1 mS/cm^{-1} (1 mmho/cm) = 1 dS/m = 1000 μS/cm (1000 micromhos/cm)

- Conductivity to mmol (+) per liter:

$$\text{mmol } (+)/1 = 10 \times \text{EC (EC in dS/m)}$$

  for irrigation water and soil extracts in the range of 0.1 to 5 dS/m.

- Conductivity to osmotic pressure in bars:

$$\text{OP} = 0.36 \times \text{EC (EC in dS/m)}$$

  for soil extracts in the range of 3 to 30 dS/m.

- Conductivity to mg/1:

$$\text{mg/1} = 0.64 \text{ (EC in dS/m)}$$

or

$$\text{mg/1} = 640 \times \text{EC}$$

  for waters and soil extracts having conductivity up to 5 dS/m.

- mmol/1 (chemical analysis) to mg/1: multiply mmol/1 for each ion by its molar weight and obtain the sum.

Note: The SI unit of conductivity is siemens (symbol S) per meter. The equivalent non-SI unit is mho and 1 mho = 1 siemens. Thus for those not used to the SI system mmhos/cm can be read for dS/m without any numerical change.

From Abrol et al., 1988. FAO Soils Bull. 39:18. With permission from the Food and Agriculture Organization of the United Nations.

2. Sodium status: Sodium status is determined as the ratio of exchangeable Na^+ to the total cation exchange capacity of the soil; the term used is exchangeable sodium percentage (ESP). Thus:

$$\text{ESP} = \frac{\text{Exchangeable Sodium (cmol kg}^{\pm 1}) \times 100}{\text{Cation Exchange Capacity (cmol kg}^{\pm 1})}$$

   When the ESP value is 15, the soil pH is 8.5 or above. Higher ESP values increase soil pH to 10.0.

   Since determination of ESP is time consuming, a more easily measured characteristic is the sodium absorption ratio (SAR), which gives the ratio of the concentrations of Na^+, Ca^{2+}, and Mg^{2+} in an extract usually obtained by suction from a satured soil. It is calculated as follows:

$$\text{SAR} = [\text{Na}]^+ \Big/ \left[1/2\left(\text{Ca} + \text{Mg}\right)^{2+}\right]^{1/2}$$

   where $[Na^+]$, $[Ca^{2+}]$, and $[Mg^{2+}]$ are concentrations of these ions in cmol kg^{-1} soil. The relationship between ESP and SAR is shown in Figure 7.1. The SAR is also used to characterize the sodicity hazard of irrigation water added to soils.
3. pH: A soil is said to be an alkali soil or "sodic soil" when the pH of the saturation extract is above 8.5. For making this determination, soil is placed in a beaker and distilled water is gradually added while stirring the contents of the beaker until a saturated soil paste is made. A suction filter is then used to obtain a sufficient amount of the extract (often the same extract is used for SAR determination).

Soil water content in the field normally fluctuates between the permanent-wilting percentage (lower end) and field capacity (upper end); the upper end is approximately two times the lower end. Measurements in soil indicate that, over a considerable textural range, soil water content at saturation percentage (SP) is approximately four times that at 1.5 MPa (permanent wilting percentage) (Table 7.3) (USDA, 1954). Thus the soluble salt concentration measured in saturation extract tends to be nearly one-half the concentration of the soil solution at field capacity and about one-fourth of the concentration at permanent-wilting percentage. The salt dilution effect that occurs due to high water-retention capacity of fine-textured soils is thus accounted for. EC_e is therefore considered a reasonable approximation of the salt concentration that the growing plants encounter in soils.

7.3. CLASSIFICATION

Salt-affect soils can be broadly classified as below:

1. Saline soils: These are the soils that contain sufficient amounts of neutral soluble salts (chlorides and sulfates of Na, Ca, and Mg) to

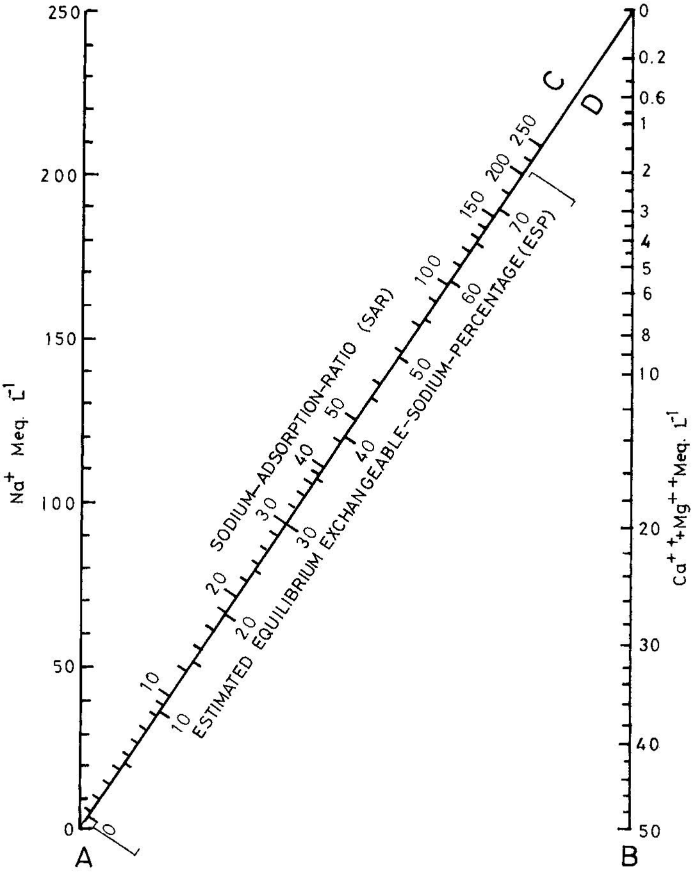

Figure 7.1. Nomogram for determining the SAR value of a saturation extract and for estimating the corresponding ESP value of soil at equilibrium with the extract (From USDA, 1954).

adversely affect the growth of most crop plants. EC_e of such soils is more than 4 dSm^{-1} and SAR is less than 13 to 15 (ESP less than 15). pH of saturation extract of these soils is less than 8.5 (Table 7.4).

2. Sodic soils: These soils (also known as alkali soils) contain sufficient sodium salts to give a saturation extract pH above 8.5. EC_e of these soils is less than 4 dSm^{-1}, and SAR is more than 13 to 15 (ESP more than 15) (Table 7.4). Sodium concentration in these soils could be very high, and the soil pH may rise to 10.0. Soils with SAR values between 5 and 13 to 15 may exhibit various aspects of sodicity, such as alkaline pH, moderate dispersion and crusting, and reduced infiltration.
3. Saline-sodic soils: These soils have mixed characteristics of both saline and sodic soils. While soil pH is less than 8.5, the EC_e may be

Table 7.3 Relation of Saturation Percentage (SP) to 1.5 MPa Water Content as Influenced by Soil Texture

Soil group	Soil samples (number)	1.5 MPa			SP			SP/1.5 MPa			SD
		Min.	Max.	Av.	Min.	Max.	Av.	Min.	Max.	Av.	
Coarse	10	3.4	6.5	5.0	16.0	43.1	31.8	4.68	8.45	6.37	1.15
Medium	23	6.6	14.2	10.8	26.4	60.0	42.5	3.15	5.15	3.95	.48
Fine	11	16.1	21.0	18.5	41.8	78.5	59.5	2.03	4.26	3.20	.60
Organic	18	27.6	51.3	37.9	81.0	255	142	2.53	4.97	3.66	.75

Adapted from USDA, 1954. SD, standard deviation.

Table 7.4 Important Characteristics of Saline, Sodic, and Saline-Sodic Soils

Soil	Saturation extract pH	Electrical conductivity (dS m^{-1})	Sodium adsorption
Saline	<8.5	>4	<13–15
Saline-sodic	<8.5	>4	>13–15
Sodic	>8.5	<4	>13–15

more than 4 dSm^{-1} and SAR more than 13 to 15 (ESP more than 15) (Table 7.4).

7.4. RECLAMATION AND MANAGEMENT OF SALINE SOILS

Saline soils are sometimes recognized by the presence of a white salt crust on the surface during hot summer months. However, gypsiforous soils may also have a white crust, but the restricted solubility of gypsum limits EC_e to about 2.8 dSm^{-1}. Also, as mentioned earlier, some black mellow soils may be saline if salts have hydrolyzed and precipitated humic materials in the surface. During the crop growth period saline soils are generally characterized by spotty growth of crop plants, often with a blue-green tinge. In the field there may be barren spots and plant growth is generally stunted. Moderate salinity can often go undetected because it causes no apparent injuries. Succulent leaves with a darker, blue-green color could be an indication, but the final judgment can be made after soil analysis. Plants in salt-affected soils often have symptoms similar to those for stress (drought) conditions, although plants may not wilt because the osmotic potential of the soil solution usually changes gradually and plants adjust their internal salt content to maintain turgor and thus avoid wilting.

The reclamation of saline soils centers around removal of excess salt from these soils. Methods commonly adopted are scraping, flushing, leaching, and drainage.

7.4.1. Scraping

This refers to the mechanical removal of salts using the available tools. Disposal of scraped salts poses a problem. Thus this method has limited applicability.

7.4.2. Flushing

Washing away the salts by flushing water over the surface can be and is sometimes used to desalinize soils, but has limited application because only

a small fraction of accumulated salt can be flushed away; a large part moves down the profile with water.

7.4.3. Leaching

Leaching salts out of the active root zone of crops is the most effective way to reclaim saline soils. For this purpose the first and foremost requisite is to have a reliable estimate of the quantity of water required to accomplish leaching of salts. The major factors determining the amount of water needed for leaching are (1) the initial salt content of the soil; (2) the desired level of salt content for good growth of crop plants; (3) the depth to which reclamation is required; (4) soil characteristics such as texture, permeability, etc.; and (5) the crop and its variety to be grown. Where groundwater tables are within a few m of the soil surface, leaching without drainage will have little lasting effect on soil salinity.

A useful rule of thumb is that a unit depth of water will remove nearly 80% of salts from a unit soil depth (Abrol et al., 1988). Thus 1 m-ha water will remove 80% of salts from the top 1 m of soil from one hectare of land. However, soil properties, particularly texture, are important and for reliable estimates it is desirable to conduct salt-leaching tests on a limited area and prepare leaching curves. Results of such a test in Iraq (Dieleman, 1963) are shown in Figure 7.2. These data show that for reducing salt content to 20% of the initial amount (removal of about 80% of the salts), the depth of leaching water required per unit depth of soil was less than 0.5 on Dujailah (silt loam, loam), about 0.75 at Dalmaj (clay to silty clay), and about 1.6 at Annanah (silty clay).

Regarding methods of leaching, sprinkling is better than flooding. Because of a slower wetting rate under sprinkling, the zone of complete leaching at the end of irrigation extends more deeply into the profile than under flood irrigation. Results comparing sprinkler vs. flooding confirm that the salts removed per unit quantity of water leached can be increased appreciably by leaching at soil water contents of less than saturation (Figure 7.3). Also when flooding is used as a method of leaching salts, more salts move upward and accumulate in the soil surface on evaporation (as shown by dashed line in Figure 7.3). Nielsen et al. (1966) showed that 25 cm of sprinkled water reduced the salinity of the upper 60 cm of soil to the same degree as 75 cm of ponded water.

7.4.4. Drainage

One of the most important requirements of the management of the saline soils is that the desired salt concentration in the root zone achieved by leaching is maintained for long periods. To achieve this, evaporation from groundwater must be prevented by keeping the groundwater table below the depth that will cause rapid soil salinization. Provision of adequate drainage is the only way to control the groundwater table. In addition to surface drainage, adequate subsurface drainage is essential. This is normally achieved by the use of open

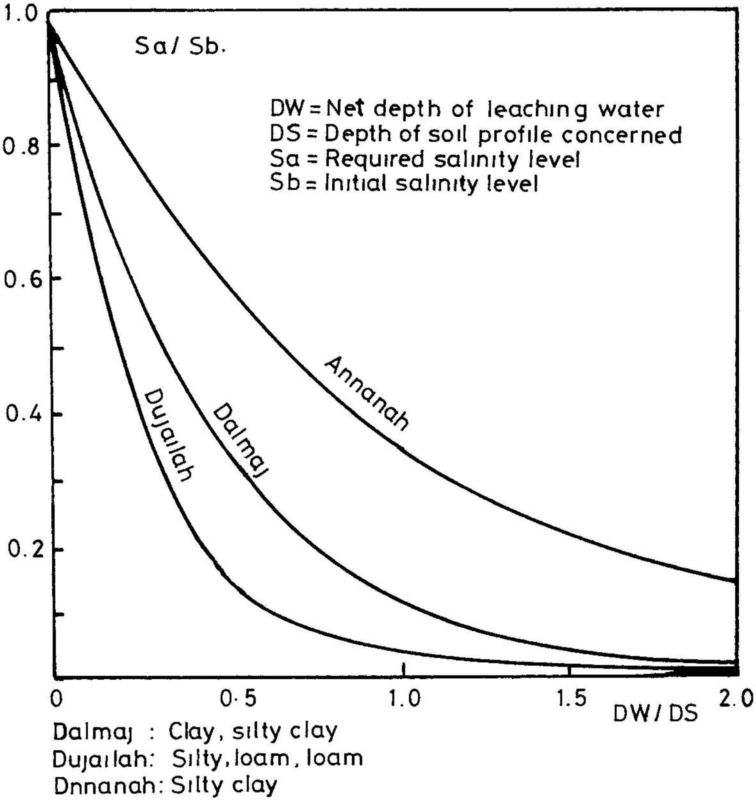

Figure 7.2. Typical leaching curves for soils in Iraq (From Dieleman, 1963. International Institute for Land Reclamation and Improvement, Wageningen. With permission from Food and Agriculture Organization of the United Nations.)

drain ditches or with buried tiles. For dryland saline seeps, salinity buildup from seepage of salt-laden water is prevented by cropping the recharge area above the seep with deep-rooted perennial crops such as grasses or alfalfa (Brown et al., 1982).

When irrigation is available and used for crop production, careful planning can help considerably to overcome the salinity problem. When furrow irrigation is practiced, most salts accumulate on the top of the ridge. Planting seeds on the sides of the ridges can help to overcome the salinity problem and permit satisfactory germination. Thus where soil and farming practices permit, furrow planting may help in obtaining better crop stands and yields.

7.5. CROP PRODUCTION ON SALINE SOILS

Plant tolerance to salinity is usually appraised in one of three ways: (1) the ability of a plant to survive on saline soils; (2) the absolute plant growth or

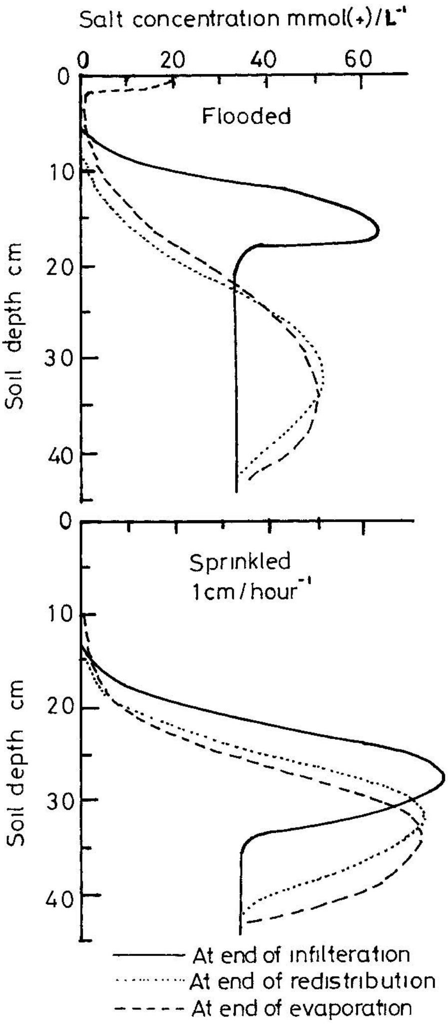

Figure 7.3. Effect of method of irrigation (flooding vs. sprinkler) and water redistribution following irrigation and evaporation on the salt concentration profiles (From Bresler and Hanks, 1969. Soil Sci. Soc. Am. Proc. 33:827–832. With permission of SSSA, Madison, WI.)

yield; and (3) the relative growth on saline soil as compared with that on nonsaline soils (Maas, 1986). Regarding the ability of plants to survive on saline soils, it may be pointed out that salinity affects plants at all stages of development, but may vary from one growth stage to another. For example, sugarbeet is more sensitive during germination, while rice, barley, wheat, corn, sorghum, and cowpea are more sensitive during early seedling growth. The

Table 7.5 Relative Salt Tolerance of Various Crops at Emergence and During Growth to Maturity

Crop		Electrical conductivity of saturated soil extract	
Common name	Botanical name	50% Yield (dS m^{-1})	50% Emergence (dS m^{-1})
Barley	*Hordeum vulgare*	18	16–24
Cotton	*Gossypium hirsutum*	17	15
Sugarbeet	*Beta vulgaris*	15	6–12
Sorghum	*Sorghum bicolor*	15	13
Safflower	*Carthamus tinctorius*	14	12
Wheat	*Tritcum aestivum*	13	14–16
Beet, red	*Beta vulgaris*	9.6	13.8
Cowpea	*Vigna unguiculata*	9.1	16
Alfalfa	*Medicago sativa*	8.9	8–13
Tomato	*Lycopersicon lycopersicum*	7.6	7.6
Cabbage	*Brassica oleracea capitata*	7.0	13
Corn	*Zea mays*	5.9	21–24
Lettuce	*Lactuca sativa*	5.2	11
Onion	*Allium Cepa*	4.3	5.6–7.5
Rice	*Oryza sativa*	3.6	18
Bean	*Phaseolus vulgaris*	3.6	8.0

From Maas, 1986. App. Agric. Res. 1:12–26. With permission of Springer-Verlag, Berlin, Germany.

relative salt tolerance of some crops at emergence, as well as in relation to yield, is given in Table 7.5.

Maas (1986) pointed out that yield response curves provide two essential parameters sufficient for expressing salt tolerance: (1) threshold — the maximum allowable salinity without yield reduction below that for nonsaline conditions; and (2) slope — the percent yield decrease per unit increase in salinity beyond the threshold. The division for classifying crop tolerance to salinity can then be made as shown in Figure 7.4. Based on these criteria, a list of some food, fiber, forage, and vegetable crops is given in Table 7.6.

7.6. RECLAMATION AND MANAGEMENT OF SODIC SOILS

By definition sodic soils are those where sodium salts dominate, exchangeable sodium percentage (ESP) is above 15 (SAR 13 to 15), and pH is above 8.5. After a thorough survey of published data, Abrol et al. (1980) observed that for sodic soils most often an ESP of 15 to 20 is associated with a saturation paste pH of 8.2. Therefore this pH value would be more realistic for diagnostic purposes; a saturation paste pH of 8.5 is generally associated with higher

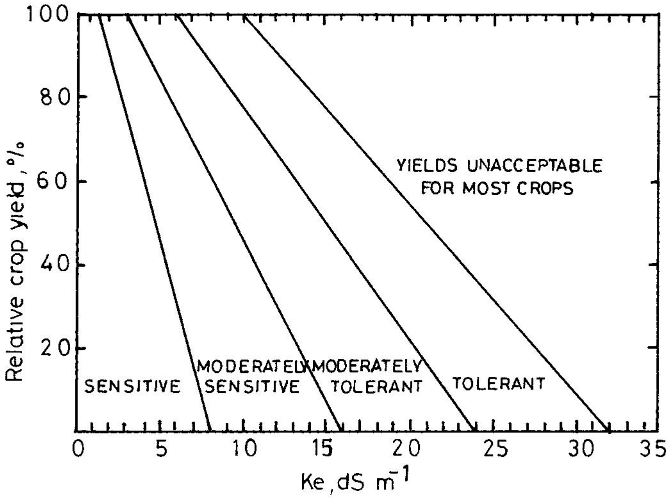

Figure 7.4. Divisions for classifying crop tolerance to salinity. Ke is EC_e, i.e., electrical conductivity of saturation extract (From Maas, 1986. App. Agric. Res. 1:12–26. With permission of Springer-Verlag, Berlin, Germany.)

values of ESP. Diagnosis at an earlier stage of sodicity is desirable. If soil pH is determined in a 1:2 soil to solution ratio, the diagnostic pH limit for sodic soils should be 9.0 instead of 8.2 as suggested for saturation paste pH (Abrol et al., 1988).

Excess exchangeable sodium in soils adversely affects plant growth in the following ways:

1. Excess exchangeable sodium has a marked adverse effect on the soil's physical properties; the soil tends to become deflocculated, and soil permeability is considerably reduced.
2. Excess exchangeable Na^+ increases soil pH, which (a) lowers the solubility of Ca and Mg carbonates, and these nutrients may become deficient; (b) increases the availability of Mo and Bo, which may reach toxic levels; and (c) decreases the availability of Zn, and this deficiency may limit plant growth.
3. Excess exchangeable sodium results in dispersion of surface soils, reduced aggregation and infiltration rate, and increased soil resistance and crusting. A general relationship between ESP and sodicity hazard is shown in Table 7.7.

Reclamation of sodic soils therefore aims at reducing the exchangeable Na to the extent that it does not degrade soil physical properties or interfere with the plant growth. For this purpose a number of soil amendments are used,

Table 7.6 Salt Tolerance of Some Food, Fiber, Forage, and Vegetable Crops

Crop	EC_e of saturation extract: Threshold ($dS\ m^{-1}$)	Slope ($\%/dS\ m^{-1}$)
Tolerant		
Barley (*Hordeum vulgare*)	8.0	5.0
Sugarbeet (*Beta vulgaris*)	7.0	5.9
Wheat-durum (*Triticum turgidum*)	5.9	3.8
Cotton (*Gossypium hirsutum*)	7.7	5.2
Bermuda grass (*Cynodon dactylon*)	6.9	6.4
Alkali grass (*Puccinellia airoides*)	—	—
Kallar grass (*Diplachne fusca*)	—	—
Salt grass (*Districhlis stricta*)	—	—
Wheat grass (*Agropyron cristatum*), fairway crested	7.5	6.9
Asparagus (*Asparagus officinalis*)	4.1	2.0
Moderately tolerant		
Sorghum (*Sorghum bicolor*)	6.8	1.6
Soybean (*Glycine max*)	5.0	20
Fescue, tall (*Festuca elatior*)	3.9	5.3
Hardingrass (*Phalaris tuberosa*)	4.6	7.6
Wheat grass (*Agropyron sibricum*), standard crested	3.5	4.0
Moderately sensitive		
Broad bean (*Vicia faba*)	1.6	9.6
Corn (*Zea mays*)	1.7	12
Peanut (*Arachis hypogaea*)	3.2	29
Sugarcane (*Saccarum officinarum*)	1.7	5.9
Alfalfa (*Medicago sativa*)	2.0	7.3
Orchard grass (*Dactylis glomerata*)	1.5	6.2
Clovers, ladino, red strawberry (*Trifolium repens, T. pratense, T. fragiferum*)	1.5	12
Broccoli (*Brassica oleracea botrytis*)	2.8	9.2
Cabbage (*Brassica oleracea capitata*)	1.8	9.7
Celery (*Apium graveolens*)	1.8	6.2
Sweet corn (*Zea mays*)	1.7	12
Cucumber (*Cucumis sativus*)	2.5	13

Table 7.6 Salt Tolerance of Some Food, Fiber, Forage, and Vegetable Crops (Continued)

Crop	EC_e of saturation extract	
	Threshold ($dS\ m^{-1}$)	Slope ($\%/dS\ m^{-1}$)
Lettuce (*Lactuca sativa*)	1.3	13
Pepper (*Capsicum annum*)	1.5	14
Potato (*Solanum tuberosum*)	1.7	12
Radish (*Raphanus sativus*)	1.2	13
Spinach (*Spinacia oleracea*)	2.0	7.6
Sweet potato (*Ipomea batatas*)	1.5	11
Tomato (*Lycopersicon lycopersicum*)	2.5	9.9
Turnip (*Brassica rapa*)	0.9	9.0
Sensitive		
Bean (*Phaseolus vulgaris*)	1.0	19
Carrot (*Daucus carota*)	1.0	14
Onion (*Allium cepa*)	1.2	16

Adapted from Maas, 1986.

Table 7.7 Exchangeable Sodium Percentage (ESP) and Sodicity Hazard

ESP	Sodicity hazard
<15	None to slight
15–30	Light to moderate
30–50	Moderate to high
50–70	High to very high
>70	Extremely high

From Abrol et al., 1988. FAO Soils Bull. 39:18. With permission from the Food and Agriculture Organization of the United Nations.

which include gypsum, calcium chloride, elemental sulfur, sulfuric acid, iron sulfate, aluminum sulfate, and pyrite. Even hydrochloric acid, available as a byproduct of the caustic soda industry, has been suggested as an amendment (Ahmad et al., 1986).

7.6.1. Gypsum

Gypsum is a mineral that occurs extensively as a natural deposit in semiarid and arid regions. For use as an amendment it needs to be ground to a reasonable particle size (to pass about a 2-mm mesh). The chemical formula

is $CaSO_4 \cdot 2H_2O$. Gypsum has a low solubility (0.25% in water) and therefore does not easily leach out. When applied and incorporated into soil (15 cm of surface soil is considered enough; incorporation into deeper layers may be less advantageous as part of it may be utilized in neutralizing soluble carbonates at the expense of replacement of exchangeable Na), it reacts with sodium salt, as well as replaces exchangeable Na, which is then leached out as sodium sulfate. The following reactions occur in soil:

a. $Na_2CO_3 + CaSO_4 \rightarrow CaCO_3 + Na_2SO_4\text{(leachable)}$

b. $\begin{matrix} Na \\ Na \end{matrix}\left[\text{clay micelle}\right] + CaSO_4 \rightarrow Ca\left[\text{clay micelle}\right] + Na_2SO_4\text{(leachable)}$

Both the above reactions are reversible, so adequate leaching arrangements have to be made to leach out sodium sulfate.

Sandoval et al. (1972) demonstrated that for sodic (solinetzic) soils containing a gypsum layer within 0.7 m of the surface, deep plowing would bring the gypsum to the surface, reducing ESP considerably and permitting profitable crop production. Several million ha of such soils exist in the Great Plains, and thousands of ha have been deep plowed in Alberta, Canada.

7.6.2. Sulfur

When elemental powdered sulfur (yellow) is applied in soil, it is oxidized by sulfur oxidizing bacteria (*Thiobacillus thiooxidans*) to SO_3^{2-}, which, when dissolved in water, produces sulfuric acid. Sulfuric acid then reacts with calcium carbonate (which is generally present in such soils) and forms calcium sulfate. The following reactions occur:

a. $2\ S + 3O_2 \rightarrow 2\ SO_3$

b. $SO_3 + H_2O \rightarrow H_2SO_4$

c. $H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + H_2O + CO_2$

d. $\begin{matrix} Na \\ Na \end{matrix}\left[\text{clay micelle}\right] + CaSO_4 \rightarrow Ca\left[\text{clay micelle}\right] + Na_2SO_4\text{(leachable)}$

7.6.3. Pyrite

Pyrite (FeS_2) is a waste material of the steel industry and can therefore be available to farmers at a fairly low cost. This material has been widely used in India. Naturally occurring pyrite minerals also occur. Pyrite oxidation (see Chapter 11 on sulfur) produces H_2SO_4, which reacts with $CaCO_3$ in soil as explained above and produces $CaSO_4$.

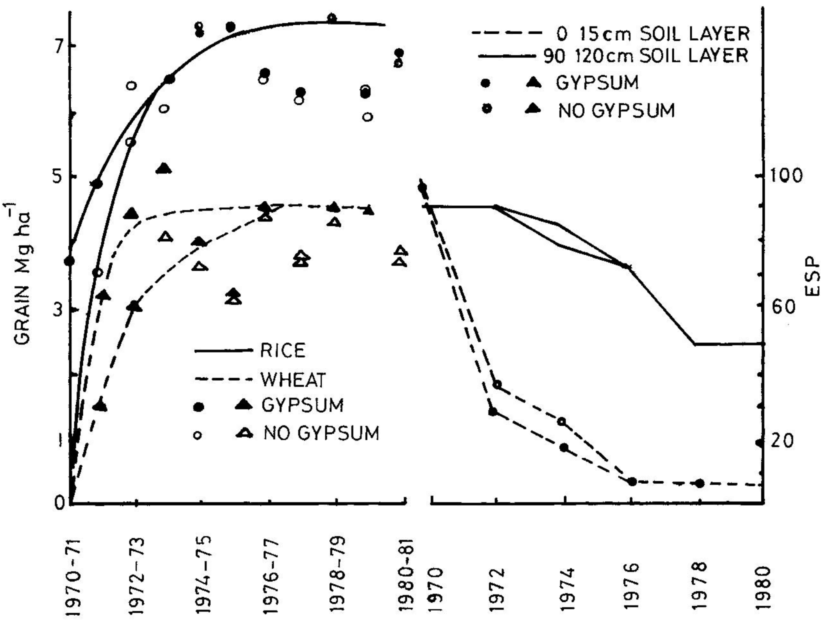

Figure 7.5. Effect of gypsum treatment on grain yield of rice and wheat and exchangeable sodium percentage (ESP) in a sodic soil from 1970 to 1980. (Drawn from the data by Singh and Abrol, 1988).

As regards their effects on soil properties and yield of rice and wheat, pyrite was found to be about one-fourth as effective as gypsum (Verma and Abrol, 1980a,b).

7.7. CROP PRODUCTION ON SODIC SOILS

Crops differ considerably in their sensitivity to sodicity. In general, grain legumes (beans) are very sensitive; cereals (other than rice and barley), cotton, sugarcane, and forage legumes such as *Trifolium alexandrinum* and *Melilotus parviflora* are less sensitive; and grasses, however, such as Bermuda grass (*Cynodon dactylon*), Rhodes grass (*Chloris gayana*), Para grass (*Brachiaria mutica*), Karnal grass (*Diploachne fusca*), barley, rice, alfalfa (*Medicago sativa*), green manuring legume dhaincha (*Sesbania aculeata*), and sugarbeet are fairly tolerant.

The tolerance of rice is primarily due to its ability to grow in standing water. Adding large masses of water lowers the concentration of sodium in the soil solution and thereby lowers pH to near neutrality (see Figure 6.3). The adverse effects of sodicity in lowering soil permeability are also to the advantage of the rice crop. Long-term field studies in India have shown that when rice was included in the crop sequence, there was a gradual reduction in sodicity so that in a period of about 10 years the upper 1.2 meters of soil was nearly free of the sodicity problem (Singh and Abrol, 1988) (Figure 7.5).

Amunson and Lund (1985) measured selected properties of a naturally saline and sodic soil in San Joaquin Valley, California, in pedons that had been reclaimed a minimum of 0, 5, 8, 15, or 25 years. More than 7.2×10^4 kg ha^{-1} of soluble salt was leached from the upper 1 m of the soil profile after 5 years, with a little or no additional removal with time. A steady-state soil solution composition was reached after approximately 15 years, as indicated by EC values of the saturation extracts. The authors also found that the smectite minerals were unstable in the reclaimed soils and were transformed to kaolinite, which thus resulted in the reduced dispersibility of the clay fraction and which may influence water infiltration in these soils.

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